Analysis of Spacing of Streaky Structures within the Surface Layer above a Real Urban

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Streaky structures within the ABL

- Roll vortices
  (shear & buoyancy driven)

- Low speed streaks
  (shear driven)

(Kanda 2012)

- Transport momentum, heat, moisture and air pollutants
**Flat surface**
- Hutchins and Marusic, 2007, JFM
- Marusic et al., 2010, Science

**Cubical surface**
- Castillo et al., 2011, BLM
- Inagaki et al., 2012, BLM

- Log layer
- Canopy layer

✓ Streaks are important phenomena to model near wall turbulence
1. Occurrence frequency and condition of streaky structures

2. Similarity of spacing of streaky structures
### Scope of this study

#### 1. Long-term observation over a urban

Studies about streaky structures using Doppler lidars

<table>
<thead>
<tr>
<th>Short term observation</th>
<th>Long term observation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>urban</strong></td>
<td>Drobinsky et al. 1998</td>
</tr>
<tr>
<td></td>
<td>Drobinsky et al. 2004</td>
</tr>
<tr>
<td><strong>sub urban</strong></td>
<td>Newsom et al. 2008</td>
</tr>
<tr>
<td></td>
<td>Iwai et al. 2008</td>
</tr>
<tr>
<td><strong>rural or sea</strong></td>
<td>Atlas et al. 1986</td>
</tr>
<tr>
<td></td>
<td>Ferrare et al. 1991</td>
</tr>
</tbody>
</table>

#### 2. Similarity in three scopes

- **Stability**
  - ✓ unstable
  - ✓ neutral
  - ✓ stable

- **Scale**
  - ✓ ABL(DL, LES)
  - ✓ wind tunnel

- **Surface**
  - ✓ flat
  - ✓ urban
Deployment of instruments

Doppler lidar (agl 55m)
- horizontal scan
- vertical scan \( \Rightarrow z_i \)

Sonic anemometer (agl 25m)
- turbulent statistics
- stability

Tokyo bay

8.7 km
(1) Occurrence frequency and condition of streaky structures
6 groups in visual classification

flows with CS (coherent structures)

1. Streak
2. Mixed
3. Fishnet

flows without CS

4. No streak
5. Front
6. The others

All flows
- 9/25-12/31 (2012)
- 7578 snapshots
6 groups in visual classification

- 9/25-12/31 (2012)
- 7578 snapshots

All flows

flows with CS (coherent structures)
- 1. Streak
- 2. Mixed
- 3. Fishnet

flows without CS
- 4. No streak
- 5. Front
- 6. The others
6 groups in visual classification

- Include
  - Roll vortices
  - Streaks

All flows
- 9/25-12/31 (2012)
- 7578 snapshots

flows with CS (coherent structures)
1. Streak
2. Mixed
3. Fishnet

flows without CS
4. No streak
5. Front
6. The others
Streak is common flow

- Streak accounts for more than 50% of all possible flows.
Atmospheric condition of flow patterns

with CS
- Streak
- Mixed
- Fishnet

without CS
- No streak
- The others

Plots of each flow pattern are clustered in areas
✓ Streak appear with larger $U$ and more neutral condition

1 plot corresponds 30mins.
Atmospheric condition of flow patterns

with CS

- Streak
- Mixed
- Fishnet

without CS

- No streak
- The others

(a) unstable

(b) stable

\[ \frac{z_i}{L} \]

\[ U (\text{ms}^{-1}) \]

1 plot corresponds 30mins.
Atmospheric condition of flow patterns

with CS

- [●] Streak
- [●] Mixed
- [●] Fishnet

without CS

- [●] No streak
- [●] The others

(a) unstable

10000
1000
100
10
1
0.1
0.01
0.001

\(-z_i/L\)

only random cells
Grossman (1982)

only roll vortices
Grossman (1982)

(b) stable

10000
1000
100
10
1
0.1
0.01
0.001

\(z_i/L\)

14 plot corresponds
30 mins.

0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
0
1
10
100
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
0 1 10 100
only random cells
Grossman (1982)

only roll vortices
Grossman (1982)
(2) Spacing of Streaky Structures
Estimation of spacing of streaky structures ($\lambda$)
λ correlate with −z/L

1 plot corresponds 30mins. *16:00-20:00 in local time.
$\lambda$ correlate with $-z/L$

- $\lambda$ gets smaller when the stability becomes more stable (comparable to Newsom et al. 2008)

1 plot corresponds 30mins. *16:00-20:00 in local time.
Outlier plots between $\lambda$ and $-z/L$

Plots around sunset time are outlier
Plots near neutral are scattered

Larger coherent structures which developed during daytime still remain and keep the size

1 plot corresponds 30mins. *16:00-20:00 in local time.

• DL_excepting sunset*
• DL_for sunset
• LES_flat (Lin et al. 1997)
• LES_city (Huda et al.)
λ correlate with local wind shear

- DL stable ($-z/L < 0$)
- DL neutral ($0 \leq -z/L < 0.03$)
- DL unstable ($0.03 \leq -z/L$)

1 plot corresponds 30mins
λ correlate with local wind shear

- DL stable ($-z/L < 0$)
- DL neutral ($0 \leq -z/L < 0.03$)
- DL unstable ($0.03 \leq -z/L$)

Local wind shear at the height of Doppler lidar

1 plot corresponds 30mins
λ correlate with local wind shear

- DL stable ($-z/L < 0$)
- DL neutral ($0 \leq -z/L < 0.03$)
- DL unstable ($0.03 \leq -z/L$)

1 plot corresponds 30 mins

✓ λ gets smaller with increasing $\Delta U/\Delta z$

Local wind shear at the height of Doppler lidar

0.0 0.0 0.0 0.1 0.1

200 400 600 800 1000

0.0 0.0 0.0 0.1 0.1

$\lambda$ gets smaller with increasing $\Delta U/\Delta z$
\( \lambda \) correlate with local wind shear

\[ \Delta U/\Delta z \ (s^{-1}) \]

- \( \circ \) DL stable \((-z/L < 0)\)
- \( \bullet \) DL neutral \((0 \leq -z/L < 0.03)\)
- \( \bullet \) DL unstable \((0.03 \leq -z/L)\)

\( \triangle \) LES_flat (Lin et al. 1997)
\( \square \) LES_city (Huda et al.)

✓ \( \lambda \) gets smaller with increasing \( \Delta U/\Delta z \)

1 plot corresponds 30mins
\( \lambda \) correlate with local wind shear

- DL stable \((-z/L < 0)\)
- DL neutral \((0 \leq -z/L < 0.03)\)
- DL unstable \((0.03 \leq -z/L)\)

- LES\(_{\text{flat}}\) (Lin et al. 1997)
- LES\(_{\text{city}}\) (Huda et al.)
- WT\(_{\text{flat}}\) (Tomkins and Adrian 2003)
- WT\(_{\text{cube}}\) (Takimoto et al. 2013)

\( \lambda \) gets smaller with increasing \( \Delta U/\Delta z \)

1 plot corresponds 30mins
$\lambda$ correlate with local wind shear

Dimensional parameters isn’t proper to discuss highly different scale $\lambda$

$\Rightarrow$ non-dimensional parameters are required

1 plot corresponds 30mins
Scaling of $\lambda$ and $\Delta U/\Delta z$

- $\lambda/z_i$
- $(\Delta U/\Delta z)/(u_*/\kappa z_i)$

- DL stable ($-z/L < 0$)
- DL neutral ($0 \leq -z/L < 0.03$)
- DL unstable ($0.03 \leq -z/L$)

- LES-flat (Lin et al. 1997)
- LES-city (Huda et al.)
- WT-flat (Tomkins and Adrian 2003)
- WT-cube (Takimoto et al. 2013)

$\phi_M \times (z/z_i)^{-1}$

shear function
Scaling of $\lambda$ and $\Delta U/\Delta z$

Regardless of stability, surface roughness and scale, the non-dimensional spacing of streaky structures can be related to non-dimensional wind shear.
Conclusions

Visual classification of flow patterns

• Streaks appear throughout a day and account for more than 50% of all possible flows.

Spacing of streaky structures ($\lambda$)

$\lambda$ vs. $-z/L$

• $\lambda$ gets smaller when the atmosphere gets more stable.
• But, plots around sunset time and near neutral are outliers.

$\lambda$ vs. $\Delta U/\Delta z$

• $\lambda$ gets smaller with increasing $\Delta U/\Delta z$.
• But $\lambda$ of wind tunnel experiments are confined in a extremely small range.

$\lambda/z_i$ vs. $(\Delta U/\Delta z)/(u_z/z_i)$

• Regardless of stability, surface roughness and scale, the non-dimensional spacing of streaky structures can be related to non-dimensional wind shear.

Thank you for your attention
Acknowledgement

• This work was supported by JSPS KAKENHI Grant Numbers 25249066.

• Kanda laboratory staff and members.

• You for your kind attention.


APPENDIX
### Occurrence number of each flow pattern

<table>
<thead>
<tr>
<th></th>
<th>Streak</th>
<th>Mixed</th>
<th>Fishnet</th>
<th>No streak</th>
<th>Front</th>
<th>The others</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>autumn</strong></td>
<td>2,351</td>
<td>699</td>
<td>130</td>
<td>613</td>
<td>28</td>
<td>227</td>
</tr>
<tr>
<td></td>
<td>(59%)</td>
<td>(17%)</td>
<td>(3%)</td>
<td>(15%)</td>
<td>(0.7%)</td>
<td>(6%)</td>
</tr>
<tr>
<td><strong>winter</strong></td>
<td>1,806</td>
<td>463</td>
<td>134</td>
<td>808</td>
<td>5</td>
<td>314</td>
</tr>
<tr>
<td></td>
<td>(51%)</td>
<td>(13%)</td>
<td>(4%)</td>
<td>(23%)</td>
<td>(0.1%)</td>
<td>(9%)</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>4,157</td>
<td>1,162</td>
<td>264</td>
<td>1,421</td>
<td>33</td>
<td>541</td>
</tr>
<tr>
<td></td>
<td>(55%)</td>
<td>(15%)</td>
<td>(3%)</td>
<td>(19%)</td>
<td>(0.4%)</td>
<td>(7%)</td>
</tr>
</tbody>
</table>

- ✓ Streak account for more than 50%
- ✓ Percentages of Mixed and No streak reverse in two seasons
Diurnal change of flow patterns

with CS  \{\text{Streak}, \text{Mixed}, \text{Fishnet}\}
without CS  \{\text{No streak}, \text{The others}, \text{Front}\}
\text{Error}  \text{Rain}

1 occurrence number corresponds 10mins.

(a) autumn
(b) winter
(1) Fluctuation of radial velocity

(2) Boundary of positive and negative radial velocity
almost straight boundary
⇒ almost homogeneous wind direction
<table>
<thead>
<tr>
<th><strong>Streak</strong></th>
<th>There is clear streaky patterns almost along the dominant wind direction. The boundary of positive and negative radial velocity is almost straight.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mixed</strong></td>
<td>There is streaky patterns almost along the dominant wind direction. The boundary of positive and negative radial velocity is distorted.</td>
</tr>
<tr>
<td><strong>Fishnet</strong></td>
<td>The boundaries of positive and negative radial velocity are periodic cell-like (fishnet) pattern.</td>
</tr>
<tr>
<td><strong>No streak</strong></td>
<td>There is no clear streaky or cell-like patterns. The boundary of positive and negative radial velocity is straight.</td>
</tr>
<tr>
<td><strong>Front</strong></td>
<td>Clear convergence line.</td>
</tr>
<tr>
<td><strong>The others</strong></td>
<td>Exception to the above five groups.</td>
</tr>
</tbody>
</table>
Atmospheric condition of flow patterns

With CS
- Streak
- Mixed
- Fishnet

Without CS
- No streak
- The others

In unstable case, patterns of CS change from Fishnet, Mixed to Streak as $U$ gets stronger and $-z_i/L$ gets smaller.

1 plot corresponds 30mins.
Atmospheric condition of flow patterns

with CS { ● Streak ○ Mixed ○ Fishnet
without CS { ● No streak ● The others

✓ In stable case, existence of CS change from The others, Streak and No streak to as $U$ gets stronger and $z_i/L$ gets smaller

1 plot corresponds 30mins.
Spacing of streaky structures

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>U (m s⁻¹)</th>
<th>u* (m s⁻¹)</th>
<th>T* (K s⁻¹)</th>
<th>z/L</th>
<th>ΔU/Δz (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 27th Sep 9:45</td>
<td>8.4</td>
<td>0.68</td>
<td>-0.027</td>
<td>-0.047</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>(b) 10th Nov 2:45</td>
<td>10.6</td>
<td>0.64</td>
<td>0.065</td>
<td>0.022</td>
<td>0.041</td>
<td></td>
</tr>
</tbody>
</table>
Diurnal change

- λ has minimum peak in early morning
- λ gets larger with getting more unstable
- λ has maximum peak around 20:00

Larger coherent structures which developed during daytime still remain and keep the size.
Relationship between $\lambda$ and $U$, $\lambda$ and $\Delta U/\Delta z$

- 3D-CDL stable ($-z/L < 0$)
- 3D-CDL neutral ($0 \leq -z/L < 0.03$)
- 3D-CDL unstable ($0.03 \leq -z/L$)

$\lambda$ vs $\Delta U/\Delta z$ (s$^{-1}$)

$\lambda$ vs $U$ (m s$^{-1}$)

Local wind shear at the height of Doppler lidar

Local wind speed at the height of Doppler lidar

Les_sky (Lin et al. 1997)

Les_city (Huda et al.)

1 plot corresponds 30mins. *16:00-20:00 in local time.*
### Surface parameters

<table>
<thead>
<tr>
<th>$\lambda_f$</th>
<th>$\lambda_p$</th>
<th>$H_{ave}$</th>
<th>$H_{max}$</th>
<th>$\sigma_H$</th>
<th>$d$</th>
<th>$z_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.29</td>
<td>0.36</td>
<td>8.4</td>
<td>45.6</td>
<td>4.1</td>
<td>14.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

![Surface parameter diagram](image.png)
Relationship among length scales (from DL & LES)

(a) $y = 0.21x$
$R^2 = 0.65$

(b) $y = 0.40x$
$R^2 = 0.10$

(c) $y = 0.64x$
$R^2 = 0.79$

(d) $y = 1.0x$
$R^2 = 0.78$

*DL : 1421 datasets with streaky structure (2012/9/25 - 2012/12/31)
<table>
<thead>
<tr>
<th>SCAN mode</th>
<th>count</th>
<th>Time (1 scan)</th>
<th>Time(sec)</th>
<th>Total (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 PPI</td>
<td>2</td>
<td>85</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>2 VRHI</td>
<td>4</td>
<td>52</td>
<td>208</td>
<td>4.6</td>
</tr>
<tr>
<td>3 PPI</td>
<td>2</td>
<td>85</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>4 RHI</td>
<td>2</td>
<td>55</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>5 PPI</td>
<td>2</td>
<td>85</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>6 RHI</td>
<td>2</td>
<td>55</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>7 PPI</td>
<td>1</td>
<td>85</td>
<td>85</td>
<td>3</td>
</tr>
<tr>
<td>8 RHI</td>
<td>1</td>
<td>55</td>
<td>55</td>
<td>2.6</td>
</tr>
<tr>
<td>9 PPI</td>
<td>2</td>
<td>85</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>10 VRHI</td>
<td>4</td>
<td>52</td>
<td>208</td>
<td>4.6</td>
</tr>
<tr>
<td>11 PPI</td>
<td>2</td>
<td>85</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>12 RHI</td>
<td>2</td>
<td>55</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>13 PPI</td>
<td>2</td>
<td>85</td>
<td>170</td>
<td>4</td>
</tr>
<tr>
<td>14 RHI</td>
<td>2</td>
<td>55</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>15 PPI</td>
<td>1</td>
<td>85</td>
<td>85</td>
<td>3</td>
</tr>
</tbody>
</table>
Cross-section of streaks

- height: 500m
- width (y): 4800m

Contour of $u'$

Blue area near surface corresponds to buildings ($U=0$)
Roll vortex

Streak
Visual classification

All flows
- 9/25-12/31 (2012)
- 7578 snapshots

flows with CS (coherent structures)
1. Streak
2. Mixed
3. Fishnet
4. No streak
5. Front
6. The others

flows without CS
4. No streak
5. Front
6. The others
Relationship between $\lambda$ and $-z/L$

3D-CDL
- ● excepting around sunset*
- ○ for around sunset
- + during a typhoon

LES_flat (Lin et al. 1997)
LES_city (Huda et al.)

$U_{ave}>3.5\text{m/s}$

1 plot corresponds 30mins. *16:00-20:00 in local time.
Relationship between $\lambda$ and $U$, $\lambda$ and $\Delta U / \Delta z$

- ○ 3D-CDL stable ($-z/L < 0$)
- • 3D-CDL neutral ($0 \leq -z/L < 0.03$)
- ● 3D-CDL unstable ($0.03 \leq -z/L$)

○ 3D-CDL stable ($-z/L < 0$)
- ● 3D-CDL neutral ($0 \leq -z/L < 0.03$)
- ● 3D-CDL unstable ($0.03 \leq -z/L$)

△ LES_flat (Lin et al. 1997)
□ LES_city (Huda et al.)

Local wind shear at the height of Doppler lidar

Local wind speed at the height of Doppler lidar

$U_{ave} > 3.5$ m/s

1 plot corresponds 30 mins. *16:00-20:00 in local time.
Scaling of $\lambda$ and $\Delta U/\Delta z$

- All plots follow a line by using non-dimensional local shear

$\Rightarrow$ Regardless of stability, surface roughness and scale, $\lambda$ can be scaled by non-dimensional local wind shear $U_{ave}>3.5\text{m/s}$
Relationship between $\lambda$ and $U$, $\lambda$ and $\Delta U/\Delta z$

- 3D-CDL stable ($-z/L < 0$)
- 3D-CDL neutral ($0 \leq -z/L < 0.03$)
- 3D-CDL unstable ($0.03 \leq -z/L$)

Local wind shear at the height of Doppler lidar

Local wind speed at the height of Doppler lidar

$U_{ave} > 4\text{m/s}$

1 plot corresponds 30mins.  *16:00-20:00 in local time.
Scaling of $\lambda$ and $\Delta U/\Delta z$

- $\lambda/z_i$
- $(\Delta U/\Delta z)/(u_*/\kappa z_i)$

- 3D-CDL stable ($-z/L < 0$)
- 3D-CDL neutral ($0 \leq -z/L < 0.03$)
- 3D-CDL unstable ($0.03 \leq -z/L$)
- LES_flat (Lin et al. 1997)
- LES_city (Huda et al.)
- WT_flat (Tomkins and Adrian 2003)
- WT_cube (Takimoto et al. 2013)

✓ All plots follow a line by using non-dimensional local shear

⇒ Regardless of stability, surface roughness and scale, $\lambda$ can be scaled by non-dimensional local wind shear

$U_{ave} > 4 \text{m/s}$
Impact of streaks on turbulences near the surface

**Flat surface**
Hutchins and Marusic (2007), JFM
Marusic et al. (2010), Science

- **Log layer**
- **Near-wall layer**

**Cubical surface**

- **Streak**
- **Roll vortex**

**Flushing**
(Inagaki et al. 2012)
(Takimoto et al. 2011)

Low momentum streaks and locations of flushing

✓Streaks affect flows of near the surface
• $z_m$: 25 m
• $z_0$: 0.6 m (Kanda et al., 2013)

Input parameters
$u^* = 0.32$, $z_i = 1062$ m, $\sigma_w = 0.49$, $z_0 = 0.6$, $z_m = 25$ m, $R = 50$

*atmospheric parameters are averaged value for 9/25-12/31

Output
xmax = 181.1 m, xR(R=50%) = 236 m (Kljun et al., 2004 http://footprint.Kljun.net)